<u>**MARKED UP SPECIFICATION**</u>

<u>**METHODS AND APPARATUS FOR GENERATING AND UTILIZING TRAINING**</u>

<u>**CODES IN A SPACE DIVISION MULTIPLEXING**</u> COMMUNICATION SYSTEM

5 <u>**Cross-Reference To Related Application**</u>

This application claims priority of European Patent Application No. 00310085.6, which was filed on November 13, 2000.

<u>**Background Of The Invention**</u>

Communication systems, especially of a non-wired type, share a common faith in

10 that they have to cope with the available bandwidth over the transmission path used. Numerous techniques have been developed through the years to utilize the available bandwidth as efficient as possible in order to enhance the bit rate over the transmission path. One of these techniques is so called space division multiplexing (SDM) by which a communication signal is fed and divided over a number of separate transmission paths in parallel. The communication means of the type

15 described in the opening paragraph employ this technique and for that purpose are equipped with transmission and reception means for every transmission path which is used for the exchange of the communication signal.

A problem encountered with SDM in ~~an~~ a non-wired environment is that the signals sent by the different transmitters are likely to interfere with each other such that each

20 receiver not only receives a signal from the associated transmitter but also from the other transmitters. In a simple case of two transmitters and two receivers the signals r_1 and r_2 received by the two receivers may be represented as follows:

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$$r_1 = h_1.x_1 + h_2.x_2$$

$$r_2 = h_3.x_1 + h_4.x_2$$

where x_1 and x_2 are the signals sent by both transmitters and $h_{1.4}$ are still unknown constants representing distortion and attenuation factors as well as other environmental and atmospheric

5   influences exerted on the transmitted signals during transport. More generally this may be represented as: $r_i=H_i.x_i$, where H_i is the appropriate column of a n-dimensional matrix containing the constants h_j, said dimension n being equal to the number of transmission paths used. If these constants are known, the system will be able to satisfactorily decode the signals received by the receivers and to derive the original signals x_i out of them. Accordingly it is necessary to teach the

10   system these factors before information is being sent. To this end the system is provided with training means which are capable of issuing known training codes which are packed into one or more training symbols which precede the information to be sent. Based on these training codes, the reception means will be able to calculate the constants h_j and to apply these constants to the information which follows.

15   A straightforward training scheme would be to use a predetermined training symbol and to send at least one such symbol by each transmitter consecutively while the other transmitter(s) are inactive. In this manner the receiver may calculate the first column of the above matrix from the training symbol sent by the first transmitter, the second column from the training symbol sent by the second transmitter, and so on. Hence, a system using n transmission paths will require a minimum

20   of n training symbols to recover the constants h_j. This training length is a serious problem for high rate wireless packet transmission links, because of the associated overhead which reduces the net data rate. For instance, at 100 Mbps, a 1000 byte packet has a duration of 80 µs. Using the same

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4μs symbol duration as the IEEE 802.11a standard, a system using 4 transmission paths would take a minimum training time of 16 μs, which means a significant overhead of 20%. The training overhead grows with bit rate and number of transmission paths so it partially reduces the benefits of using SDM.

5   The present invention has inter alia for its object to provide a communication system which the training time may be reduced considerably compared to the above. It is a further object of the invention to provide such a communication system with improved frame detection and frequency synchronization.

Summary of the Invention

10   The present invention relates to a communication system comprising first communication means, second communication means and a first transmission path as well as at least one further transmission path between said first and said second communication means, in which at least the first communication means are provided with transmission means for each of said transmission paths, which are capable of sending at least part of a communication signal to the

15   second communication means, in which at least the second communication means comprise reception means for each of said transmission paths, which are capable of receiving at least part of said communication signal, and in which at least the first communication means comprise training means for generating a training code to be sent to the reception means enabling the reception means to match a received signal to a corresponding transmitted signal.

20   To this end a communication system of the kind described in the above paragraph is according to the invention characterized in that the training means are capable of generating a training code with at least nearly ideal cyclic auto-correlation properties such that its cyclic auto-

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correlation function is at least nearly zero for all cyclic shifts, in that the transmission means are capable of concurrently sending said training code in a mutually shifted manner and in that the reception means are capable of performing a cyclic auto-correlation with respect to a received training signal. Because of the cyclic auto-correlation properties of the training code applied in

5 accordance with the invention it is achieved that the auto-correlation performed on the received training signal leaves no or hardly no by-products. Instead, with ideal auto-correlation properties, the output of the auto-correlation operation at the reception side will be either $n.h_i$ or zero, where h_j, is one of the constants to be estimated and n is a known normalization factor. In fact the auto-correlation properties need not be absolutely ideal but may deviate to a small extent ~~extend~~ from the

10 ideal situation, leaving sufficient certainty to derive the required constants. Because the transmitters send the training code concurrently in time, the invention, in theory, requires only one training symbol's duration to recover all constants h_i.

The auto-correlation operation requires that the training code is multiplied by all itself and by all its cyclic shifts to render the above product. This may be affected by sending not only the

15 training code but also its cyclic shifts to the reception means and multiplying these codes with the training code generated by the reception means. In a preferred embodiment, however, the communication system according to the invention is characterized in that the reception means are capable of generating the cyclic shifts of a received training code and to correlate these with said training code. In this case, only the training code has to be sent and this code as well as all cyclic

20 shifts are generated at the reception side. Not only limits this embodiment transmission time and hence training time, it also avoids any distortion or other noise of the correlation products.

A specific embodiment of the communication system according to the invention is

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characterized in that the training code comprises a concatenation of the rows of a Fourier matrix. Such a concatenation is generally referred to as a Frank and Zadoff-Chu sequences and happen to have ideal auto-correlation properties. This renders these sequences extremely suitable for use in a communication system in accordance with the present invention.

5   The length of the training code is preferably equal to the number of connection paths used or a integer multiple thereof.

In yet another specific embodiment, the communication system according to the invention is characterized in that the training code y is derived from a maximal length sequence x with an uneven length L, having an auto-correlation of –1 for all cyclic shifts, such that at least

10   approximately $y = x + j/oL$. A maximal length sequence has an auto-correlation of –1 for all cyclic shifts. A sequence of this kind with an uneven length can be modified into the above code y which is suitable for use in the communication system according to the invention.

In order to deal with possible delay spread of the training signals received by the second communication system, a further embodiment of the communication system according to the

15   invention is characterized in that, during operation, the training codes are preceded and followed by a dummy code. The dummy codes are taken sufficiently long to avoid substantial overlap between the auto correlation output signals during the training stage, so that the constants may be derived unambiguously.

In a further preferred embodiment, the communication system according to the

20   invention is characterized in that the training means comprise a pre-correction filter for processing the training code. A pre-correction filter as used in this embodiment is not absolutely necessary, but without it the reception means generally will have to perform a correction. The additional

complexity and possible signal noise may be saved by pre-correcting the training signals before they are being sent.

In a further preferred embodiment, the communication system according to the invention is characterized in that the training means comprise storage means for storing one or more training codes. The transmitted training signal can be pre-calculated and stored in memory to avoid the complexity of a separate pre-correction filter which would otherwise be used merely during the training phase. The pre-corrected training codes are for instance stored in a lookup table easily accessible for the training means. During the training stage, these codes merely need to be read out so that no complex circuitry is needed for generation or pre-correction of the codes concerned.

In still a further preferred embodiment of the communication system according to the invention not merely one training code is issued during the training phase but instead the training means, during operation, issue a number of at least substantially identical training codes and in that the receiving means comprise summation means to average the received training codes. By issuing a repetition of training codes and adding the auto-correlation output over time, a significant improvement in signal to noise ratio may be obtained.

The use of a repetitive pattern of the same code as training signal, moreover provides an excellent frame detection trigger. To this end, a further specific embodiment of the communication system according to the invention is characterized in that the training means, at least during operation, issue at least substantial training codes at a substantially fixed interval and in that the reception means are provided with auto correlation means for correlating a received signal with one or more signals received after a delay corresponding to said interval or an integer multiple thereof. Because of the ideal auto-correlation properties of the code, the correlation outputs consist

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only of the sum of n_t auto-correlation points, whereas all cross-correlation products between signals

coming from different transmitters are zero. If there is a valid training signal at the input of the

reception means, then the correlator output values are proportional to the total received power on

each reception means. The phase of the correlator outputs is equal to $2Bf_oT_c$, where f_o is the

5   frequency offset between transmission means and the reception means and T_c the time interval

between successive training codes. After summing all correlator outputs, a start of a frame is

detected by looking if the magnitude of the output signal exceeds some threshold. The value of the

threshold is a tradeoff between the probability of a false alarm and the detection probability. If a

start-of-transmission is detected, then the phase of the summed correlator outputs is a measure for

10   the carrier frequency offset that can be fed to a frequency correction circuit. The frequency offset f_o

is given by the output phase divided by $2BT_c$.

Brief Description of the Drawings

The invention will be described in further detail below along the lines of a specific

example and with reference to the accompanying drawings. The drawings show in:

15   Figure 1 is a schematic representation of a specific embodiment of a communication

system in accordance with the invention;

Figure 2 is the in phase part of the correlation output of an receiver upon reception of

a training signal within the system of Figure 1 for two transmit antennas;

Figure 3 is the windowed correlation output of Figure 2;

20   Figure 4 is the in phase channel coefficient for different sub-carriers, both estimated

and actual, in the system of Figure 1;

Figure 5 is a first embodiment of a frame detection and frequency synchronization

circuit for use in a communication system according to the invention;

Figure 6 is a second embodiment of a frame detection and frequency synchronization circuit for use in a communication system according to the invention; and

Figure 7 is a third embodiment of a frame detection and frequency synchronization

5   circuit for use in a communication system according to the invention.

Like parts have been given the same reference numerals throughout the figures.

Detailed Description

The communication system depicted in Figure 1 comprises first communication means 10 with transmission means which are capable of sending a communication signal in a

10   wireless communication network as well as second communication means 20 which comprise reception means which are capable of receiving said communication signal. In this example, the communication means are primarily intended for data exchange and operate based on a TCP/IP or any other suitable packaged data transmission protocol.

Especially with data transmission the finite available bandwidth presents an

15   everlasting limitation. In order to cope with this limitation, several multiplexing techniques have been developed, including space division multiplexing (SDM) as used in this example. According to the technique, the transmission means comprise multiple transmitters 11..14 which are concurrently used for the transmission of the communication signal over multiple transmission carriers, whereas also multiple reception means 31..34 are available for receiving the signals sent. The different

20   transmission means 11.14 and reception means 31..34 each comprise their own antenna, which is depicted schematically in the drawing. Moreover, a division of the signal over several orthogonal frequency bands is effected in order to further enhance the capacity of the system, generally known

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as orthogonal frequency division multiplexing (OFDM). The communication system is distributed over the different sub-carriers and frequencies to maximize the data throughput capacity of the connection.

SDM used in wireless data transmission presents a complication in that the signals of the different transmission means 11.14 will inevitably be received by all reception means 31.34. For four transmitters 11..14, like in this example, sending signals $x_1..x_4$ respectively on a specific sub-carrier, the signals $r_1..r_4$ received by the different receivers 31..34 are given by:

$$r_1 = h_1.x_1 + h_2.x_2 + h_3.x_3 + h_4.x_4$$

$$r_2 = h_5.x_1 + h_6.x_2 + h_7.x_3 + h_8.x_4$$

$$r_3 = h_9.x_1 + h_{10}.x_2 + h_{11}.x_3 + h_{12}.x_4$$

$$r_4 = h_{13}.x_1 + h_{14}.x_2 + h_{15}.x_3 + h_{16}.x_4$$

in which $h_1..\cancel{16}_{16}$ represent transmission factors or channel coefficients which take into account the spatial displacement of the different transmitters and receivers as well as different environmental influences giving rise to, for instance, attenuation and distortion of the signal. Because these factors are not known and may change from time to time, they need to be recovered for each data package being sent. This process is generally referred to as channel training and consists of the transmission of a number of known data signals which enable the reception means to recover the transmission factors $h_{1..16}$. To this end, the transmission means are equipped with training means 21..24. Although these training means are indicated separately for all transmitters, they may be shared among the transmitters in order to save circuitry.

The training means may comprise a processor unit capable of calculating the appropriate training signals, but in this example, simply consist of a look-up table which has been

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filled in advance with suitable training codes. In accordance with the present invention, these

training codes are chosen to have at least nearly ideal auto-correlation properties, meaning that their

auto-correlation product is zero for all cyclic shifts and non-zero for itself. In this example, the so-

called Frank and Zadoff-Chu sequence is taken as training code. A Frank code is obtained by

5   concatenating all rows or columns of a discrete Fourier matrix. The 4 by 4 discrete Fourier matrix F,

for example, is given by:

$$F = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & j & -1 & -j \\ 1 & -1 & 1 & -1 \\ 1 & -j & -1 & j \end{bmatrix}$$

By concatenating the rows of this matrix, the following sequence c is obtained having

perfect auto-correlation properties:

10          $c = \{1, 1, 1, 1, 1, j, -1, -j, 1, -1, 1, -1, 1, -j, -1, j\}$

The auto-correlation function of this code renders zero for all its cyclic shifts and

equals 16 for the non-shifted auto-correlation. In this example, use is made of a code c with a length

(16) equal to an integer multiple (4) of the number of sub-carriers (4).

The same training code c is supplied to all transmitters 11..14, but in a cyclically

15   shifted fashion. This means that, for instance, the first transmitter 11 transmits the original code c,

the second transmitter 12 transmits the code cyclically shifted over one digit, the third transmitter 13

transmits the code c shifted over two digits, and so on. In order to compensate for any distortion

during transmission, a pre-correction filter is applied to the code c so that its spectrum will be the

same as that of the OFDM signal. It is not absolutely necessary to add a pre-correction but, without

20   it, the receivers need to make a correction which would make the channel estimates more noiser for

sub-carriers corresponding to low code spectral values of the transmitted code. The corrected

training signal is precalculated and stored in the look-up table of the training means 21..24 to avoid

the complexity of a separate pre-correction filter which would otherwise only be used for the training

phase.

5   The second communication means 20 comprise separate receivers 31..34 with

associated antennas for all transmitters 11..14 of the first communication means 10. These receivers

31..34 will each receive the training codes c coming from all transmitters 11..14. The receivers are

each coupled to correlation means 41..44 which perform a cyclic correlation of the code c with part

of the signal received by the associated receiver 31..34 of a length equal to the code c. If the training

10   length is more than twice the code length, then the receivers ~~may~~ 31..34 first sum or average an

integer number of parts of the training signal with a <u>length</u> ~~lengths~~ equal to that of the code c. The

averaged signal is then used to perform the cyclic correction. Because of the ideal cyclic auto-

correlation properties of the training code c, as used in the communication system according to the

invention, at all times, only the signal of one of the transmitters 11..14, matching the code at that

15   time applied by the cyclic correlation means 41..44, will deliver a non-zero output whereas the

signals received from the other transmitters will be cancelled. By cyclically shifting the code c, all

coefficients may be recovered in this manner, one after the other.

Figure 2 shows an example of the cyclic correlation output for two transmitters. The

cyclic correlation output shows separate impulse responses for different transmission antennas,

20   which are separated by a delay equal to the cyclic shift applied in the subject transmitter. The code

in this example is a length 64 Frank sequence that is two times over sampled, so there are 128

samples in one code length. All receivers will see a different cyclic correlation function from which they can extract the channel information.

To estimate a specific channel coefficient h̶j̶ h_j the reception means comprise a filter 51..54 which isolates the impulse response of the subject transmitter by multiplying the cyclic

5   correlation output of the correlator 41..44 by a window function which is non-zero only at the desired impulse response. The window has smooth roll-off regions in order to minimize errors in the estimated channel frequency response. The roll-off factor is a compromise between frequency leakage and delay spread robustness; a larger roll-off region gives less frequency leakage but it also attenuates more impulse response components whose path delays fall within the roll-off region.

10   Figure 3 shows an example of a windowed correlation function based on the correlator output shown in Figure 2.

The windowed impulse response, taken at the output of the filter 51..54, is cyclically shifted back by a second correlator 61..64 to compensate for the cyclic shift applied to the transmitter. Finally, the channel frequency response is found by calculating a Fast Fourier Transform

15   (FFT) over the windowed impulse response, taken at the output of the second correlator 61..64. To this end, the reception means comprise a FFT-filter 71..74. The FFT-filter 71..74 outputs resemble the channel coefficient values of all OFDM sub-carriers for one particular transmitter-receiver pair. The estimated channel frequency response for all sub-carrier is drawn as curve **a** in Figure 4, whereas curve **b** represents the actual values. At the lower sub-carriers, there is minor difference with the

20   actual channel frequency response, which is assumed to be introduced by the windowing operation of the first filter 51..54.

Although the system of this example uses OFDM together with SDM, the invention may as well be used for SDM on its own, i.e. with merely a single carrier. If peak power is limited, which is often the case, then single carrier SDM training might require a separate training signal per transmit antenna instead of a common signal source. The training signal has to be long enough to get

5   sufficient signal-to-noise ratio (SNR) ratio at the receiver. Instead of sending separate training signals over the antennas one by one, one long the training signal may then be transmitted simultaneously on all antennas. In the receiver, the same procedure outlined above can be followed up to the cyclic correlation. The outputs of the cyclic correlation directly resemble the desired channel coefficients that are needed for a single carrier SDM receiver.

10   Theoretically, the training time need not be longer than the duration of the training code c. In practice however, a repetition of the training code is used in order to realize sufficient SNR at the receiver's end. Moreover, in order to deal with inevitable delay spread, the code c is preferably extended with a small dummy code preceding and following it. The addition of said dummy codes ascertains that the impulse responses associated with the different transmitters do not

15   overlap mutually. This extended code is then stored in the look-up table of the training means 21..24. Even with this extension, the total training time need not be much longer than the duration of a training signal with sufficient SNR, whereas the prior art systems all require a multiple thereof.

The fact that, in a communication system according to the invention, the training signal consists of a repetitive pattern with at least nearly ideal auto-correlation properties may also

20   advantageously be used for frame detection and the detection of the carrier frequency offset. Figure 5 shows a block diagram of a system that detects the start of a transmission and that estimates the carrier frequency offset in a communication system like that of Figure 1 but with two transmitters

and receivers. For each receiver 31, 32, the reception means comprise delay means 81, 82 to add a delay time T_c to the received signal, where T_c is equal to the duration of the training code c, and conversion means 91, 92 to convert the delayed signal to a conjugated replica of it. This T_c seconds delayed and conjugated replica is fed to correlation means 101, 102. Because of the ideal auto-

5 correlation properties of the code c, the correlation outputs consist only of the sum of n_t auto-correlation points, whereas all cross-correlation products between signals coming from other transmitters are zero.

If there is a valid training signal at the input of the receivers, then the correlator output values are proportional to the total received power on each receiver. The phase of the correlator

10 outputs is equal to $2B.f_0.T_c$, where f_0 is the frequency offset between transmitter and receiver. If all transmitters and receivers from one SDM terminal share the same reference oscillator, only a single frequency offset has to be estimated and corrected. The correlator outputs are added at 105 and fed to summation means 110 to average the total in time. A start of a frame is detected by means of a comparator 120 which detects whether the magnitude of the absolute value 115 of the output signal

15 of the summation means 110 exceeds some threshold *. The value of the threshold * is a tradeoff between the probability of a false alarm and the detection probability. If a start-of-transmission is detected, a trigger is raised at the output 130 of the circuit and at the same time the actual phase v of the summed correlator outputs is a measure for the carrier frequency offset. The frequency offset f_0 is given by the output phase v divided by $2B.f_0.T_c$ and may be derived at the output 140 of

20 calculation means 125 in order to be fed to a frequency correction circuit.

Figure 6 shows a block diagram of an SDM synchronization system that finds the symbol timing based on knowledge of the transmitted training codes c. Each of the received signals

is passed through a matched filter 151, 152 with an impulse response equal to the conjugated and time-reversed code c. Hence, the matched filter output shows the correlation between the received signal and c. As there is no knowledge of the carrier phase at this stage, the power of the correlation outputs is calculated by taking the square of the output value with suitable means 160. The power

5   outputs of all receivers are added at 165 to improve the signal-to-noise ratio (SNR) of the detector output. A further SNR enhancement is obtained by adding signal components which are spaced apart by T_d seconds 170, where T_d is equal to the cyclic time shift applied to the codes c in the SDM transmitters. The eventual output is fed to comparator 175 which selects the largest peak. The occurrence of this peak is a trigger that can be used for symbol timing.

10   Besides adding and averaging the training signals of multiple transmitters and receivers, moreover averaging over several training codes is possible to further enhance the SNR. To this end, an additional Finite Impulse Response (FIR) filter 172 is added to the circuit of Figure 6 that adds samples which are spaced apart by multiple code lengths of T_c seconds, see Figure 7. As the training signal consists of a repetition of the same code c, this further improves the SNR. The

15   circuit of Figure 7, moreover, comprises an extra FIR filter 174 that sums over multiple multipath components with a spacing of one sample interval T_s. The number of taps L of this last FIR filter should preferably be such that $L.T_s$ is equal to the maximum tolerable delay spread that the receiver can tolerate. This structure gives an enhanced SNR performance in the case of multipath fading channels. In addition, it improves the maximum tolerable delay spread.

20   Although the invention has been described in further detail with reference to merely a number of embodiments, it will be appreciated that the invention is by no means limited to the examples given. On the contrary a skilled person will be able to arrive at numerous different

embodiments and variation without departing from the scope and spirit of the present invention. As such he may avail himself of other codes with ideal or nearly ideal cyclic auto-correlation properties to be used as training codes. Besides the aforementioned Frank and Zadoff-Chu sequences, for instance maximum length sequences, having an auto-correlation of −1 for all cyclic shifts, may be

5   used as a basis of such an alternative code. By an odd length maximum length sequence.